6. *Magmatism and Metamorphism*

The Ultramafic Belts

Peter J. Wyllie

ONE petrological approach to upper mantle studies is to determine which ultramafic rocks represent mantle material. Ultramafic rocks occur in a variety of field and petrographic associations: in recent reviews, *Wyllie* [1967*b*, 1968] outlined eleven petrographic associations, some with subdivisions. In this summary, it is convenient to consider these in four larger groups: (1) layered, stratiform, and other intrusions involving gabbro or diabase, together with accumulations or concentrations of mafic minerals; (2) the alkalic rocks, including kimberlites, mica peridotites, members of ring complexes, and ultrabasic lava flows; (3) the several serpentinite-peridotite associations often classified together as alpine-type intrusions; (4) serpentinites and peridotites of the oceanic regions.

It is generally agreed that the ultramafic rocks of group 1 were formed from mantle-derived basaltic magma, and therefore they can provide only indirect evidence of mantle chemistry and mineralogy. The other groups are associated with major tectonic features of the earth's crust, and there is evidence that these rocks include representatives of the upper mantle. Kimberlites and alkalic ultrabasic ring complexes occur in stable or fractured continental regions; their distribution appears to be controlled by deep-seated tectonics with linear trends. Alpine-type ultramafic rocks are distributed along deformed mountain chains and island arcs, usually with associated gabbros or basic volcanic rocks. The occurrence of serpentinites and peridotites along mid-oceanic ridges suggests a third type of ultramafic belt.

KIMBERLITES AND ALKALIC ULTRABASIC ROCKS IN CRATONIC REGIONS

Recent reviews of these rocks have been presented by *Upton* [1967], *von Eckermann* [1967], *Davidson* [1967*a*], and *Dawson* [1967*a*, b]. Their petrogenesis is complicated by processes involving the concentration of alkalis and volatiles in residual liquids. Most investigators agree that kimberlites originate deep in the mantle. Contamination of a mantle-derived ultrabasic magma with crustal material is often invoked to explain their unusual chemistry [*Turner and Verhoogen,* 1960, pp. 249 and 396]; an alternative proposal involves reaction of a primary carbonatite magma from the mantle with 'granitic' crustal rocks to yield the alkalic ultrabasic magmas [*Dawson,* 1967*b*]. Some kimberlites and mica peridotites may be emplaced as crystal aggregates transported by gases, or a carbonatite magma, at temperatures of 600 to 700°C [*Watson,* 1967; *Franz and Wyllie,* 1967].

Kimberlite diatremes are crowded with xenoliths, including peridotites, garnet peridotites, and eclogites, which are generally interpreted as primary mantle material. *Harris et al.* [1967] proposed that the nodules represent fragments from a pyroxene-peridotite layer in the mantle, and deeper garnet-peridotite. *O'Hara*'s [1967] pyroxene grid indicates that the eclogite and garnet eclogite nodules equilibrated at depths of 100 to 140 km on the thermal gradient for shield regions. *Davidson* [1967*b*] noted the variable mineralogical composition of the nodules and the problems that this poses for interpretations of mantle mineralogy.

ALPINE INTRUSIONS IN OROGENIC REGIONS

The petrogenesis of these rocks is complex because it involves metamorphic processes: indeed, *den Tex* [1965] discussed them in terms of their metamorphic lineages rather than their igneous origin. The argument about the possible existence of ultrabasic magmas in this association is now apparently resolved in favor of solid emplacement [*Hess,* 1966, pp 5–6]; many petrologists consider that alpine intrusions represent parts of the solid, or partially fused, mantle that have flowed into or through the crust along the unstable orogenic belt [*de Roever,* 1957; *Thayer,* 1960, 1967; *Green,* 1967]. Temperatures of intrusion, or of re-intrusion, may range from that of basaltic magmas to low temperatures well within the serpentine stability field [*Green,* 1967; *Wyllie,* 1967*b*]. Geochemical evidence suggests that many alpine ultramafic rocks are derived from a part of the mantle that attained a residual character during an early period of mantle differentiation [*Murthy and Stueber,* 1967].

Thayer [1960, 1967] discussed and deplored the conceptual divorce of ultramafic and mafic rocks, and he listed six criteria that characterize the intrusive peridotite-gabbro complexes of alpine type. Reconsideration of the petrogenesis of ultramafic and mafic rocks together [*Miyashiro,* 1966] has contributed to the formulation or revival of several hypotheses. The ophiolite hypothesis interprets the complexes as massive, differentiated submarine lavas ranging in composition from ultrabasic to basic, together with some intrusive rocks. *Maxwell* [1968] discussed the great composite sheets of the Mediterranean and Himalayas, concluding that these represented extrusions of mantle rocks breaking through the sea floor. They may be as thick as 8 to 10 km.

Criteria for distinguishing alpine ultramafic rocks from those of layered intrusions have been proposed by *Thayer* [1960, 1967], but *Smith* [1958] suggested that there is a continuous series of peridotite-gabbro associations between the stratiform rocks and the alpine rocks. Several alpine peridotites have recently been interpreted as gravity-stratified crystal cumulates from basic magma [*Challis,* 1965; *Miyashiro,* 1966, quoting Nagasaki], and *O'Hara* [1967] suggested that the only feature that alpine intrusions have in common is an orogenic setting that causes tectonic transport and re-intrusion. His pyroxene grid does indicate that alpine ultramafic rocks have equilibrated under a wide range of conditions.

One group of ultramafic rocks occurring in orogenic belts has features distinguishing it from alpine and from stratiform peridotite-gabbro complexes. These are the belts of cylindrical peridotite bodies characterized by a crude concentric zoning of dunite, pyroxenites, and hornblende peridotite. *Taylor* [1967] reviewed occurrences in Alaska and the Ural Mountains; similar rocks in Japan were described by *Onuki* [1966]. Taylor concluded that they were formed by the successive intrusion of liquid ultrabasic magmas of different compositions, all with high contents of FeO, CaO, and H_2O.

This summary review indicates some of the problems involved in using alpine ultramafic rocks as a basis for discussions about the upper mantle. A more detailed review of the current hypotheses for the origin of these rocks is given in *Wyllie* [1967].

MID-OCEANIC RIDGES

In 1962, Hess developed his thesis that the main crustal layer beneath the oceans may be serpentinized peridotite, like that dredged from fault scarps on the Mid-Atlantic ridge, from the Puerto Rico trench, and collected from St. Peter's and St. Paul's rocks on the Mid-Atlantic ridge; in 1964, he reviewed the significance of this association of oceanic ultramafic rocks. Genetic links between the oceanic association and the alpine ultramafic belts are indicated by *Hess'* [1960] proposal that the serpentinites of Puerto Rico represented uplifted oceanic crust, which 'may be altered mantle rocks exposed at the surface' (p. 235), and by *Dietz'* [1963] suggestion that a spreading ocean floor could cause tectonic incorporation of the serpentinite of the oceanic crust into overlying sediments of the continental rise, thus producing ultramafic rocks of alpine type when the sedimentary pile was metamorphosed.

Maxwell [1968] drew attention to similarities between the basic pillow lavas and peridotites which appear to characterize the mid-oceanic ridges, and the extrusion of mantle material in the ophiolite complexes of alpine mountain belts. Continued study of the mid-oceanic ridges may well confirm that they are the locus of ultramafic belts quite as extensive as the alpine ultramafic belts, but separated from them by an ocean basin.

DISCUSSION

For petrological information about the mantle, we must examine the rocks in the ultramafic belts, which occupy regions where hot mantle material and magma have approached or reached the surface as a result of major tectonic processes, with linear controls.

The alkalic rocks in the cratonic ultramafic belts do not provide direct representatives of the mantle because they have been strongly fractionated. For example, in kimberlites, the abundance of elements such as K, Rb, Sr, Ba, U, Th, C, and H indicates a general enrichment of up to 200-fold compared with any likely mantle parent (P. G. Harris, personal communication). However, the xenoliths carried upward in the kimberlite diatremes are promising candidates for mantle samples.

The alpine ultramafic rocks of the orogenic belts probably include representative mantle material, but the prospect that some of these intrusions are derived from cumulates in basic stratiform intrusions, or in volcanic conduits, indicates that caution is required in their interpretation. The effects of metamorphism blur the petrogenesis of the alpine peridotite-gabbro associations.

The ultramafic rocks of the mid-oceanic ridges, when they are adequately sampled, may perhaps provide the best prospects for direct correlation with upper mantle material. There are no stratiform intrusions known in this belt to confuse interpretation, and the history of the ultramafic rocks has not been obscured by orogenic metamorphism.

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Batholiths and Their Orogenic Setting

Ahti Simonen

BATHOLITHS of granitoid rocks occur in the folded belts of the earth's crust where interaction between the upper mantle and the crust has been active. Because of the close relationship between batholith emplacement and orogenic folding, the batholiths are commonly classified into preorogenic, synorogenic, late orogenic, postorogenic, and anorogenic groups. The batholiths, whose emplacement is due to intrusion, are crystallized either from juvenile or anatectic magmas rising upward into the folding belt. Juvenile granitic magmas derive from the upper mantle, and anatectic magmas have originated by partial remelting of the granitic crust and geosynclinal sediments in the zones of tectonic activity where deviations from the thermal equilibrium state of the crust have taken place. The metasomatic granitization of older rocks has been caused by granitic material migrating upward in the earth's crust. This has played an important rôle in the origin and emplacement of the batholiths in the migmatite front. Granite magmas and the granitic material causing the granitization are derived from greater depths by upward migration of light granitic elements. The ultimate origin of the granite and the granitic crust is connected geophysical monograph 13

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